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A NEW MILKY WAY DWARF GALAXY IN URSA MAJOR

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ABSTRACT

In this Letter, we report the discovery of a new dwarf satellite to the Milky Way, located at $(\alpha_{2000}, \delta_{2000})$ = (158.72,51.92) in the constellation of Ursa Major. This object was detected as an overdensity of red, resolved stars in Sloan Digital Sky Survey data. The color-magnitude diagram of the Ursa Major dwarf looks remarkably similar to that of Sextans, the lowest surface brightness Milky Way companion known, but with approximately an order of magnitude fewer stars. Deeper follow-up imaging confirms this object has an old and metal-poor stellar population and is $\sim$ 100 kpc away. We roughly estimate M_V = -6.75 and $r_{1/2}$ = 250 pc for this dwarf. Its luminosity is several times fainter than the faintest known Milky Way dwarfs. However, its physical size is typical for dSphs. Even though its absolute magnitude and size are presently quite uncertain, Ursa Major is likely the lowest luminosity and lowest surface brightness galaxy yet known.

Subject headings: galaxies: Local Group – galaxies: dwarf

1. INTRODUCTION

A complete census and study of nearby dwarf galaxies is vital to our global understanding of galaxy formation. Dwarf galaxies are the most numerous type of galaxy in the Universe and are thought to be the "building blocks" of larger galaxies. Milky Way (MW) dwarf galaxies are particularly interesting because they are close enough for HST to resolve their stellar populations fainter than their main sequence turnoffs. This enables precise measurements of dwarfs' structural parameters, metallicities, and detailed star formation histories when coupled to wide-field ground-based imaging. MW dwarfs are also close enough for ground-based spectroscopy to measure the metallicities and velocities of individual stars.

The existence (or lack) of dwarf galaxies fainter than those known also holds promise to substantially improve our understanding of the "substructure problem". Cold dark matter models predict more than an order of magnitude more low mass dark matter halos than the number of dwarf galaxies observed around galaxies such as our own (Klypin et al. 1999; Moore et al. 1999). The fraction of low-mass halos that may host a luminous galaxy is reduced by baryonic physics such as reionization, feedback, and tidal effects. However, possible incompleteness in the census of MW dwarf galaxies at the faint end hinders our interpretation of such models, leaving open the possibility that they do not produce the true population (Willman et al. 2004).

To improve the completeness of the known Milky Way dwarf galaxy population, we have been conducting a search for Milky Way satellites in the Sloan Digital Sky Survey (SDSS; Willman et al. 2002). Careful analyses of resolved stars in both SDSS and 2MASS have already resulted in the discovery of a new Milky Way companion (Willman et al. 2005a) and a faint M31 dwarf satellite (Zucker et al. 2004), as well as large-scale stellar structures and dwarf galaxy remnants around the Milky Way (Newberg et al. 2002; Yanny et al. 2003; Ibata et al. 2003; Rocha-Pinto et al. 2003, 2004; Majewski et al. 2004; Martin et al. 2004). However, it has been more than 10 years since the discovery of the ninth Milky Way dwarf spheroidal galaxy (Ibata et al. 1994; but see evidence in Martin et al. 2004 and Martinez-Delgado et al., in prep, for a probable new Milky Way dwarf at low latitude). In this Letter, we report the discovery of the Ursa Major dwarf (UMa dSph), the tenth dwarf spheroidal companion to the Milky Way.

2. DATA AND RESULTS

2.1. *Sloan Digital Sky Survey Data*

The Sloan Digital Sky Survey (SDSS; York et al. 2000), is a spectroscopic and photometric survey in 5 passbands (u, g, r, i, z; Fukugita et al. 1996; Gunn et al. 1998; Smith et al. 2002), that has thus far imaged thousands of square degrees of the sky. Data is reduced with an automatic pipeline consisting of: astrometry (Pier et al. 2003); source identification, deblending and photometry (Lupton et al. 2001); photometricity determination (Hogg et al. 2001); calibration (Fukugita et al. 1996; Smith et al. 2002); and spectroscopic data processing (Stoughton et al. 2002).

The Ursa Major dSph was found as part of a systematic search for Milky Way companions. It was detected as

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a statistically significant fluctuation at $(\alpha_{2000}, \delta_{2000}) \sim$ (158.72,51.92) in the number of stars with $19.0 < r < 20.5$ having colors consistent with red giant branch stars. The data relevant for this discovery are publicly available in Data Release 2 of the SDSS (DR2, Abazajian et al. 2004). See Willman et al. (2002); Willman et al. (2005b) for details of our automated search technique, detection limits, and the summarized survey results.

Figure 1 shows color-magnitude diagrams (CMDs) created solely with SDSS data of the Ursa Major dSph (both before after a statistical subtraction of field stars; left and middle panels) and the Sextans dSph (right panel). Sextans is an old and metal-poor ([Fe/H] = -2.1; Lee et al. 2003) Milky Way dSph at a distance of 86 kpc. There are a total of 172 stars in the 200 arcmin^2 detection area plotted in the left panel, but only 50 remain after field subtraction. Probable red giant branch stars are outlined in the middle panel, and the overdensity at $r \sim 20.5, -0.1 < g - r < 0.5$ is a probable horizontal branch. We overplot the stellar locus of the Sextans dSph empirically derived from SDSS data on its CMD.

A visual comparison of the Sextans and UMa CMDs shows that they are strikingly similar. The UMa dSph CMD has roughly an order of magnitude fewer stars than the Sextans CMD, and thus it must have a much lower surface brightness if it truly is an analogous object. This is remarkable given that Sextans is the lowest surface brightness Milky Way dwarf known, having $\mu_V = 26.2$ mag arcsec^{-2} (Mateo 1998), and that the lowest surface brightness dwarf currently known has $\mu_V = 26.8$ mag arcsec^{-2} (Zucker et al. 2004). We overplot the stellar locus of the Sextans dwarf projected to 100 kpc on Ursa Major's CMD in Figure 2.

2.2. *Isaac Newton Telescope Data*

To confirm the Ursa Major dwarf as a Sextans-like Milky Way companion, we obtained follow-up imaging with the 2.5m wide-field camera on the Isaac Newton Telescope (INT) on 2005 March 6-8. Figure 3 shows a CMD in Harris B and Sloan r of stars in a $23' \times 12'$ arcmin field around the center of UMa from a total of 5300 seconds of exposure time in B and 3000 seconds in r. The magnitudes were calibrated by comparison to SDSS data. We overplot the theoretical isochrone of an [Fe/H] = -1.7, 13 Gyr old population (Girardi et al. 2004) projected to 100 kpc. We used the Smith et al. (2002) transformations to convert the Girardi isochrone in Sloan filters from g and r to B and r. In addition to the sparse horizontal and red giant branch seen in the SDSS, a sub-giant branch becomes clear in these deeper data at $21.5 < B < 23.0$ and $B - r \sim 0.9$, confirming UMa as a new MW companion. A main-sequence turnoff (MSTO) also appears near $B \sim 24.5$ and $B - r \sim 0.5$. The horizontal branch and MSTO are separated by almost 4 magnitudes in B, characteristic of an old stellar population. A detailed analysis of all the INT data will be presented in a subsequent paper.

2.3. $r_{1/2}$ *and* M_V

The spatial distribution of red giant branch (RGB) stars outlined in Figure 1 supports the idea that UMa is a new nearby dwarf. Its RGB stellar distribution, shown in the left panel of Figure 4, is very similar in angular extent to the spatial distribution of Sextans' RGB stars, shown in the right panel of Figure 4. Based on this distribution, the half-light radius of Ursa Major is $\sim 7.75'$ ($r_{1/2} \sim 250$ pc, assuming a distance of 100 kpc). This estimated half-light radius is very similar to that of Sextans, which has $r_{1/2} \sim 200$ pc (Mateo 1998).

To estimate the absolute magnitude of UMa, we first sum the luminosities of stars in Figure 2 (assuming a distance of 100 kpc) to estimate its faintest possible absolute magnitude $M_{\rm V,faint} = -4.6$. We then apply an approximate correction to this minimum luminosity by multiplying it by 2 to account for object stars outside the 200 arcmin^2 detection area and then multiplying by 3 to account for stars that fall below the SDSS magnitude limit. These multiplicative factors are uncertain and were estimated by measuring the fraction of light coming from stars brighter than the horizontal branch in Sextans and Palomar 5 as observed by SDSS. This approximation yields $M_{\rm V,corr}$ = -6.5. Similarly, we compare the number of stars in UMa's RGB to the number of stars in Sextans'. UMa has $\sim$ 10 stars brighter than its horizontal branch after field subtraction, whereas Sextans has $\sim$ 100. From this comparison, we estimate $M_{\rm V}$ = -7.0, because Sextans has $M_{\rm V}$ = -9.5. This size and absolute magnitude is extremely uncertain, and are only intended to give a sense of UMa's possible properties.

3. DISCUSSION

The absolute magnitude of the UMa dSph is fainter than those of the faintest known dwarfs but is similar to those of some known globular clusters. However, five of the nine known MW dSphs have absolute magnitudes that also overlap with those of globular clusters. The half-mass size of the Ursa Major dwarf is also quite similar to those of the known Milky Way dSphs, but is nearly an order of magnitude larger than those of either the largest Milky Way globular clusters (Harris 1996) or the newly discovered extended star clusters around M31 (Huxor et al. 2004). UMa is also more distant than all but one of the MW globular clusters. We thus conclude that UMa is a new Milky Way dwarf spheroidal galaxy.

There is no clear connection between the UMa dwarf and any known object. The new galaxy is near $(l, b) = (160, 54)$, which is not proximate to any of the known MW dwarfs or globular clusters. UMa does appear to be located along the great circle possibly traced by the Ursa Minor dSph tidal stream, but is more distant. UMa is also coincidentally located only a few degrees away from SDSS J1049+5103, another recently discovered Milky Way companion (Willman et al. 2005a). However, it is nearly a factor of two times farther away.

UMa was detected very close to our detection limits. Numerous other dwarfs with properties similar to or fainter than the Ursa Major dSph may thus exist around the Milky Way. Although no reliable extrapolation can be made from a single object, the fact that at least one new Milky Way dwarf was detected in $\sim$ 4700 deg^2 ($< 1/8$) of the sky suggests it is reasonable to expect that 8-9 additional dwarfs brighter than our detection limits still remain undiscovered over the entire sky. If true, that number would preclude models that do not predict the presence of many ultra-faint dwarfs. However, our survey only included sky at $|b| > 30$. In a scenario where Milky Way dwarfs are intrinsically biased to lie at high latitude (Zentner et al. 2005), we would extrapolate a smaller total number of dwarfs based on this single detection.

We are in the process of obtaining and analyzing deep, wide-field imaging of UMa. With these deeper data, we will obtain estimates of its age and metallicity, as well as measure its detailed spatial distribution to derive its surface brightness, scale size, and search for tidal features.

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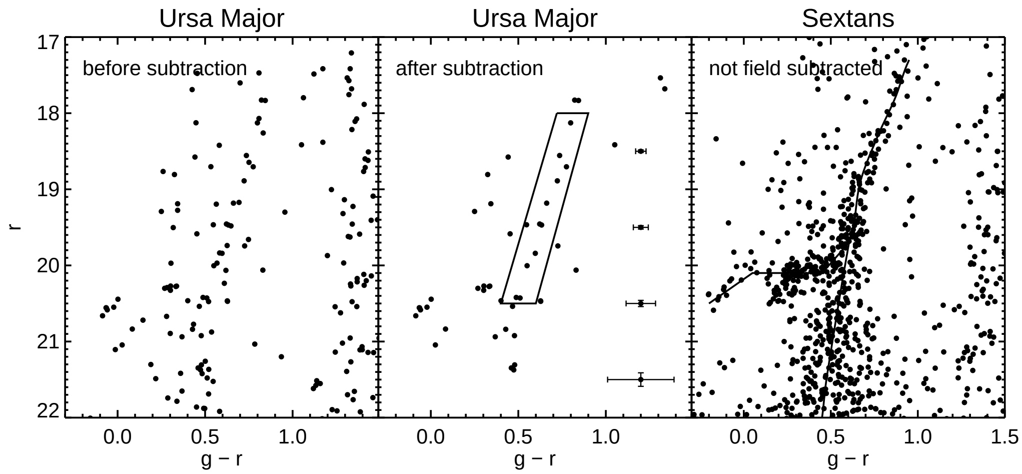

Fig. 1.— *Left Panel:* Ursa Major CMD including all 172 stars within the 200 arcmin^2 area included in the detection, without a statistical subtraction of foreground stars. *Middle Panel:* Field subtracted CMD of UMa. The probable red giant branch of UMa is outlined. *Right Panel:* The color-magnitude diagram of the Sextans dSph ($\mu_V = 26.2$, $d = 86$ kpc) without any field star subtraction. This CMD includes all stars within Sextans' half-light radius and was created solely with SDSS data. The stellar locus of Sextans, empirically measured with the SDSS data, is overplotted. All three CMDs and the field subtraction were created solely with SDSS data.

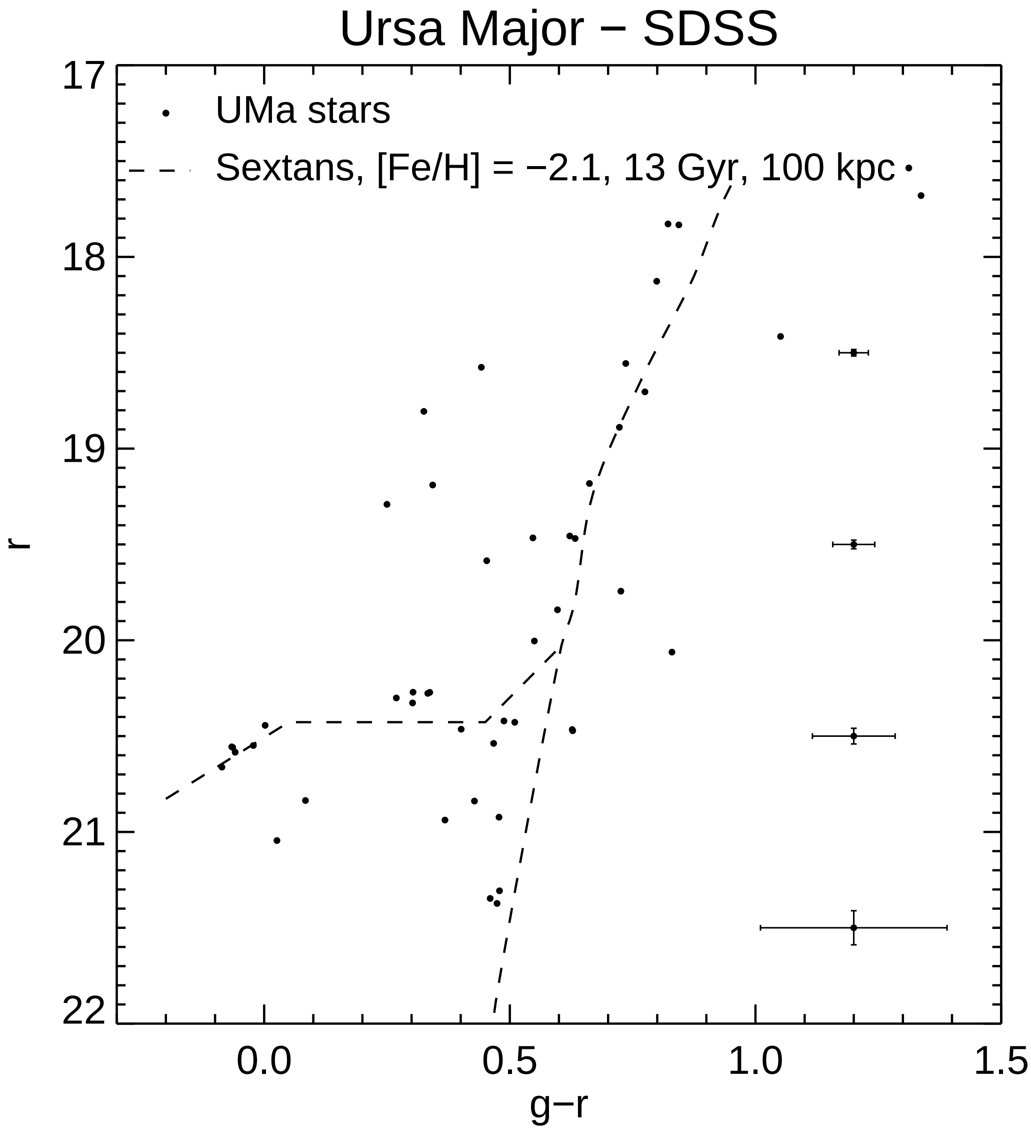

Fig. 2.— The field subtracted color magnitude diagram of Ursa Major. The stellar locus of Sextans stars, empirically measured with SDSS data and projected to 100 kpc is overplotted. Typical color errors as a function of magnitude are shown at the right.

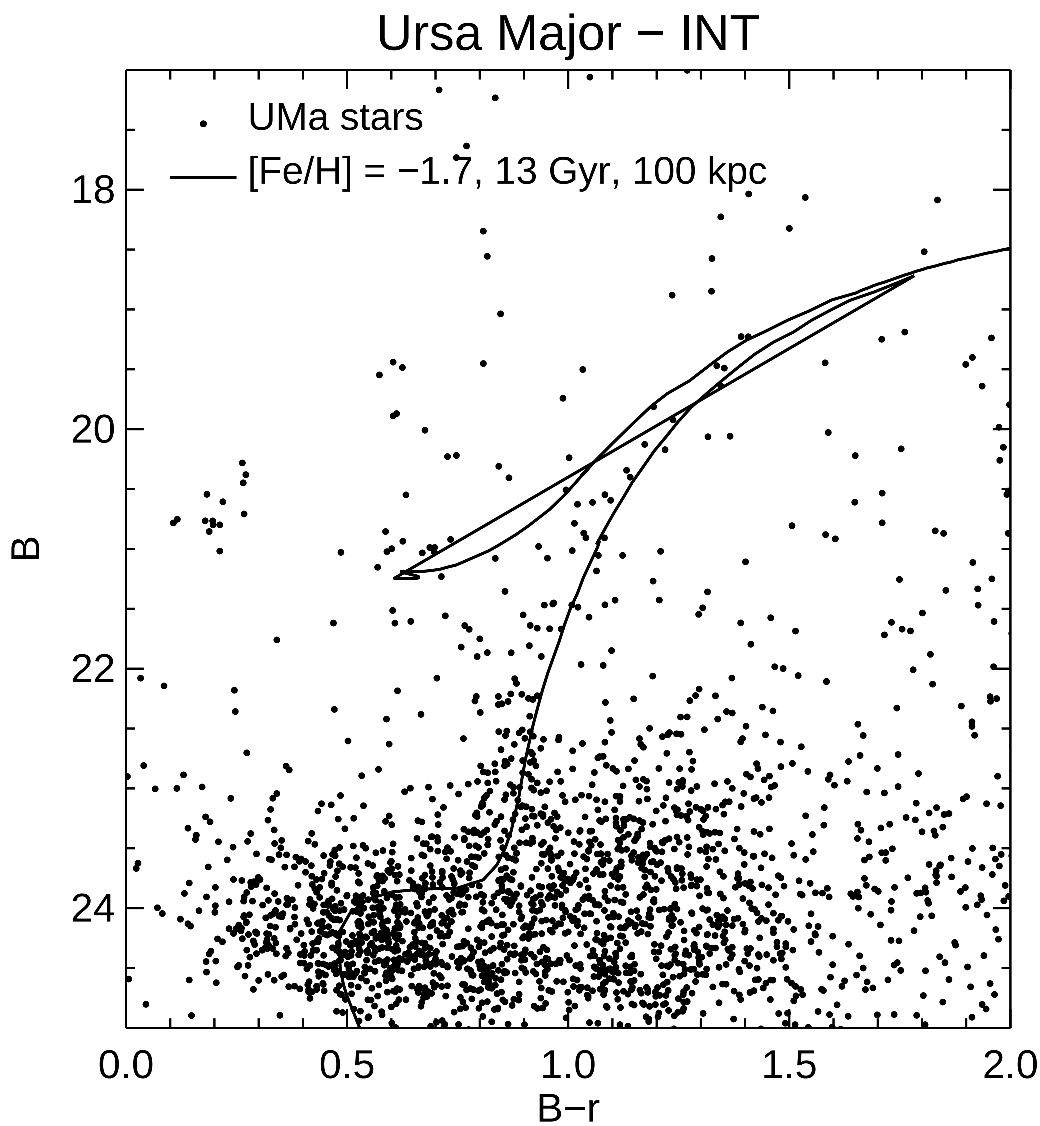

FIG. 3.— The CMD of stars in an 23′ × 12′ field around the center of Ursa Major, as observed in a total of 5400 seconds of exposure time in B and 3000 seconds in r. A theoretical isochrone of an [Fe/H] = -1.7, 13 Gyr old population is overplotted (Girardi et al. 2004).

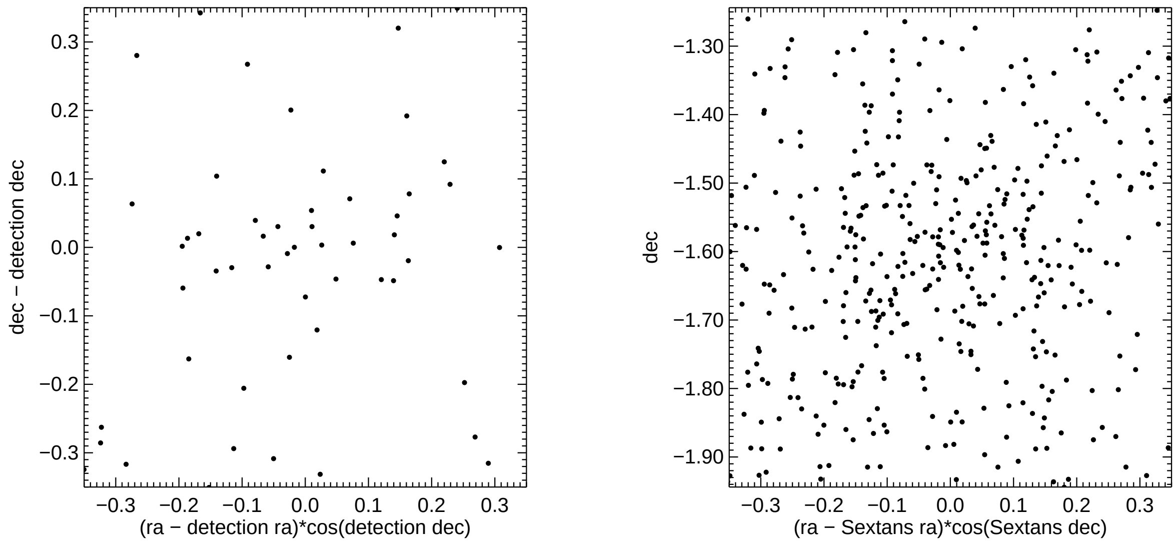

FIG. 4.— *Left Panel:* The spatial distribution of Ursa Major as traced by the red giant branch stars outlined in the middle panel of Figure 1. The stellar overdensity appears to extend over nearly 0.25 square degrees, and its half-light radius is approximately 7.75′. *Right Panel:* For comparison, the spatial distribution of stars in the Sextans dSph (d = 86 kpc) that fall in the same region of the color-magnitude diagram.